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# IN-FLIGHT EVALUATION OF THE LATERAL HANDLING OF A FOUR-ENGINE JET TRANSPORT DURING APPROACH AND LANDING

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16. Abstract

As part of a program to document the stability, control, and flying qualities of jet transport airplanes, the lateral handling of a typical jet transport was evaluated during up-and-away and approach flight in the landing configuration. Sidestep maneuvers to a landing were performed with several levels of lateral control power in smooth-air conditions. A roll control power capability of about 15 deg/sec$^2$ was required for satisfactory lateral control, but 61-meter (200-foot) lateral offsets to the runway could be safely corrected with very low levels of lateral control power, approximately 2 to 5 deg/sec$^2$, using altered piloting techniques. The pilot evaluation results were in general agreement with results from other studies.

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**Page 19:** In table 3, the roll inertia, $I_X$, should be multiplied by 10:

| | 140 knots | 180 knots |
|---|---|---|
| $I_X$ (estimated), kg-m$^2$ (slug-ft$^2$) . . . . | 2,412,000 (1,780,000) | 2,588,000 (1,910,000) |

The inertias used in the calculations were correct.

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# IN-FLIGHT EVALUATION OF THE LATERAL HANDLING OF A FOUR-ENGINE JET TRANSPORT DURING APPROACH AND LANDING

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## SUMMARY

As part of a program to document the stability, control, and flying qualities of jet transport airplanes, the lateral control required for correcting lateral-offset approaches in smooth air to landings was investigated by making simulated lateral-offset approaches at 3048 meters (10,000 feet) altitude and actual lateral-offset approaches to landings in a typical jet transport. Roll control power of about 15 deg/sec$^2$ was required for satisfactory roll handling for approach. Lateral offsets could be corrected with roll control power as low as 2 to 5 deg/sec$^2$. However, piloting techniques were used that might not be operationally satisfactory for all approach situations, and the pilots rated the low roll capability as unacceptable (pilot rating of approximately 8). Although the results of the study allowed more time to bank than specified by the revised Military Specification for transports, the results were in general agreement with those of other studies. The level of roll control power rated to be satisfactory during simulated approaches at altitude was rated satisfactory during actual landings. The level of roll control power rated to be unsatisfactory or unacceptable during simulated approaches at altitude was rated more unsatisfactory or unacceptable during actual approaches.

## INTRODUCTION

To investigate the flight characteristics of jet transport airplanes, a typical four-engine, swept-wing jet transport was flown throughout its certified flight envelope. Stability and control response data were obtained at representative flight conditions and analyzed for the determination of static and dynamic stability and control derivatives. Minimum flight speeds were investigated and are reported in reference 1. The lateral control requirements for transports during approach and landing were considered during part of the study. The approach phase of flight was selected because that flight condition has dictated the lateral control requirements for many configurations and because it is a critical phase of flight in which a high percentage of accidents occur.

A simulated instrument approach with a "breakout" at an altitude of 61 meters (200 feet) and a 61-meter (200-foot) lateral offset to the runway provided a realistic maneuver for evaluation by the pilots. Pilot evaluations and ratings were obtained during the program. A range of lateral control required for the approach and landing of transport airplanes of the approximately 45,000-kilogram to 90,000-kilogram (100,000-pound to 200,000-pound) class in smooth-air conditions was investigated.

These results are compared with results of the simulation of a large transport aircraft (ref. 2), the results of other more general studies (refs. 3 and 4), the Military Specification for piloted airplanes (ref. 5), and design recommendations for transport aircraft (ref. 6).

## SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U. S. Customary Units. The measurements were taken in U. S. Customary Units. Factors relating the two systems are presented in reference 7.

| | |
|---|---|
| $h$ | altitude, m (ft) |
| $I_X$ | rolling moment of inertia about body X-axis, kg-m$^2$ (slug-ft$^2$) |
| $I_Z$ | yawing moment of inertia about body Z-axis, kg-m$^2$ (slug-ft$^2$) |
| $L_p$ | dimensional damping-in-roll derivative, 1/sec |
| $L_r$ | dimensional roll-due-to-yawing derivative, 1/sec |
| $L_\beta$ | dimensional roll-due-to-sideslip derivative, 1/sec$^2$ |
| $L_{\delta_a}$ | dimensional roll-due-to-aileron-control derivative (based on average aileron deflection, right roll positive), 1/sec$^2$ |
| $L_\delta \delta$ | rolling angular acceleration or roll power due to roll controls (aileron and spoiler), deg/sec$^2$ |
| $L_{\delta_r}$ | dimensional roll-due-to-rudder derivative, 1/sec$^2$ |
| $L_{\delta_s}$ | dimensional roll-due-to-spoiler derivative (based on average spoiler deflection, right spoiler up positive), 1/sec$^2$ |
| $N_p$ | dimensional yaw-due-to-rolling derivative, 1/sec |
| $N_r$ | dimensional yaw-damping derivative, 1/sec |
| $N_\beta$ | dimensional static directional-stability derivative, 1/sec$^2$ |
| $N_{\delta_a}$ | dimensional yaw-due-to-aileron-control derivative (based on average aileron deflection), 1/sec$^2$ |
| $N_{\delta_r}$ | dimensional yaw-due-to-rudder derivative, 1/sec$^2$ |

| | |
|---|---|
| $N_{\delta_s}$ | dimensional yaw-due-to-spoiler derivative, $1/\text{sec}^2$ |
| $p$ | roll rate, deg/sec |
| $p_{ss}$ | steady-state rolling velocity, deg/sec |
| $t_{30}$ | time-to-bank 30°, sec |
| $V_i$ | indicated airspeed, knots |
| $Y_\beta$ | dimensional side-force-due-to-sideslip derivative, 1/sec |
| $Y_{\delta_a}$ | dimensional side-force-due-to-aileron derivative (based on average aileron deflection), 1/sec |
| $Y_{\delta_r}$ | dimensional side-force-due-to-rudder derivative, 1/sec |
| $Y_{\delta_s}$ | dimensional side-force-due-to-spoiler derivative, 1/sec |
| $\beta$ | sideslip angle, deg |
| $\delta_w$ | wheel deflection, deg |
| $\zeta_d$ | damping ratio of the Dutch roll oscillatory mode |
| $\tau_R$ | roll time constant, sec |
| $\varphi$ | bank angle, deg |
| $\varphi_1$ | bank angle change in 1 second, deg |
| $\varphi_2$ | bank angle change in 2 seconds, deg |
| $\omega_d$ | undamped natural frequency of the Dutch roll oscillatory mode, rad/sec |
| $\omega_\varphi$ | undamped natural frequency of the numerator quadratic of the roll-to-aileron transfer function, rad/sec |

Subscript:

| | |
|---|---|
| max | maximum |

## DESCRIPTION OF AIRPLANE AND MANEUVERS

### Test Airplane

The test airplane is a swept-wing and swept-tail four-engine jet transport (figs. 1 and 2) designed for cruise at a Mach number of approximately 0.85 at altitudes up to

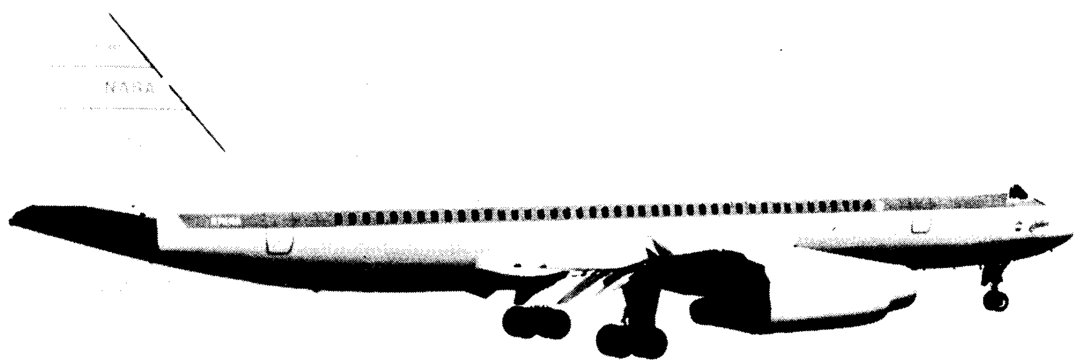

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*Figure 1. Photograph of the test airplane.*

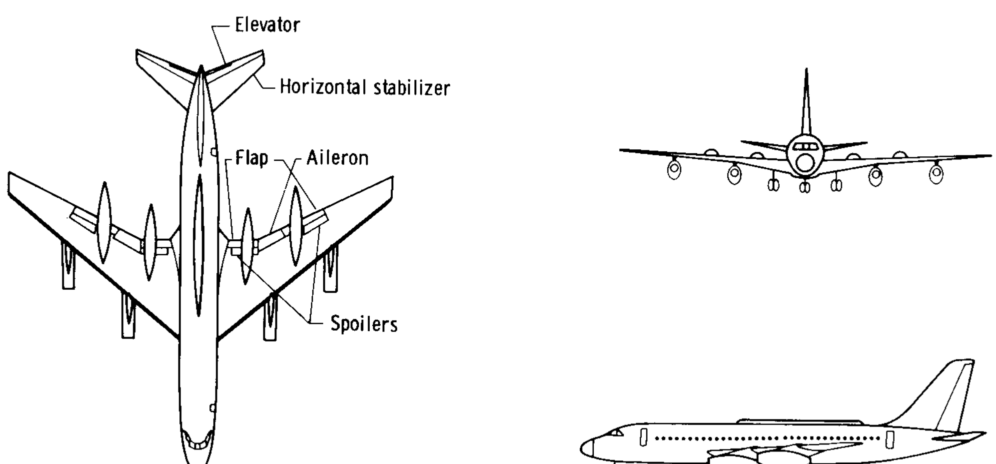



*Figure 2. Three-view drawing of the test airplane.*

about 12,000 meters (40,000 feet). The weight of the airplane was about 68,000 kilograms (150,000 pounds) or less for the evaluations of three of the four participating pilots and about 86,000 kilograms (190,000 pounds) for the remaining pilot's evaluations. The airplane response data presented were corrected to the lighter weight, 68,000 kilograms (150,000 pounds).

Airplane dimensions are given in table 1. The airplane was flown in the final approach configuration, that is, landing gear extended, wing leading-edge flaps extended, and wing trailing-edge flaps fully extended (50°). The yaw damper was not used, which is standard operating procedure for the airplane. There was no lateral damping augmentation.

TABLE 1. – PHYSICAL CHARACTERISTICS OF THE TEST AIRPLANE

| | |
|---|---|
| Fuselage - | |
| Maximum width, m (ft) | 3.51 (11.50) |
| Maximum height, m (ft) | 3.78 (12.42) |
| Length, m (ft) | 42.60 (139.75) |
| Wing - | |
| Incidence (root), deg | 4 |
| Aerodynamic span, m (ft) | 35.97 (117.99) |
| Area, $m^2$ ($ft^2$) | 209 (2250) |
| Root chord, m (ft) | 8.88 (27.15) |
| Tip chord, m (ft) | 2.69 (8.83) |
| Mean aerodynamic chord, m (ft) | 6.34 (20.81) |
| Dihedral, deg | 7 |
| Aspect ratio | 6.2 |
| Leading-edge sweep, deg | 39 |
| Horizontal tail - | |
| Area, $m^2$ ($ft^2$) | 39.6 (426.55) |
| Dihedral, deg | 7.5 |
| Leading-edge sweep, deg | 41 |
| Span, m (ft) | 11.80 (38.74) |
| Aspect ratio | 3.52 |
| Vertical tail - | |
| Area, $m^2$ ($ft^2$) | 27.4 (295) |
| Sweep at 30-percent chord, deg | 35 |
| Span, m (ft) | 6.45 (21.17) |
| Aspect ratio | 1.52 |
| Aileron - | |
| Area, $m^2$ ($ft^2$) | 2.78 (29.97) |
| Span, m (ft) | 2.93 (9.62) |
| Maximum travel, deg | ±15 |
| Inboard spoiler - | |
| Area, $m^2$ ($ft^2$) | 1.65 (17.8) |
| Mean aerodynamic chord, m (ft) | 0.85 (2.8) |
| Maximum travel, deg | 75 |
| Outboard spoiler - | |
| Area, $m^2$ ($ft^2$) | 3.86 (41.51) |
| Mean aerodynamic chord, m (ft) | 0.95 (3.11) |
| Maximum travel, deg | 60 |

<u>Aerodynamic controls</u>. – The airplane's aerodynamic controls consisted of the following movable surfaces: ailerons, spoilers, wing flaps, leading-edge flaps, elevators, horizontal stabilizer, and rudder. The primary pilot controls were ailerons, spoilers, rudder, and elevator.

The ailerons and spoilers provided lateral control. The ailerons were actuated by aerodynamic boost from pilot-controlled aileron flight control tabs. The flight tabs were deflected ±20° and commanded ±15° of aileron deflection.

Two spoilers were mounted in the top surface of each wing, forward of the inboard and outboard flaps. They were hydraulically actuated and provided about 65 percent of the total lateral control. Full travel limits of the outboard and inboard spoilers were 60° and 75°, respectively. The spoilers could be used for speed brakes and, in an emergency, for longitudinal trim. The spoiler deflection angles were limited by the hinge-moment capabilities of the actuators operating with full hydraulic pressure; however, the tests in this study were conducted below the indicated velocity limit for full spoiler deflection, so full spoiler was available. The pilot's control wheel rotation was limited mechanically for various tests in this investigation to ±45°, ±30°, or ±15°. These limitations allowed spoiler deflections of 50, 22.5, and 6.5 percent of maximum and aileron control deflections of 45, 27, and 12 percent of maximum (fig. 3).

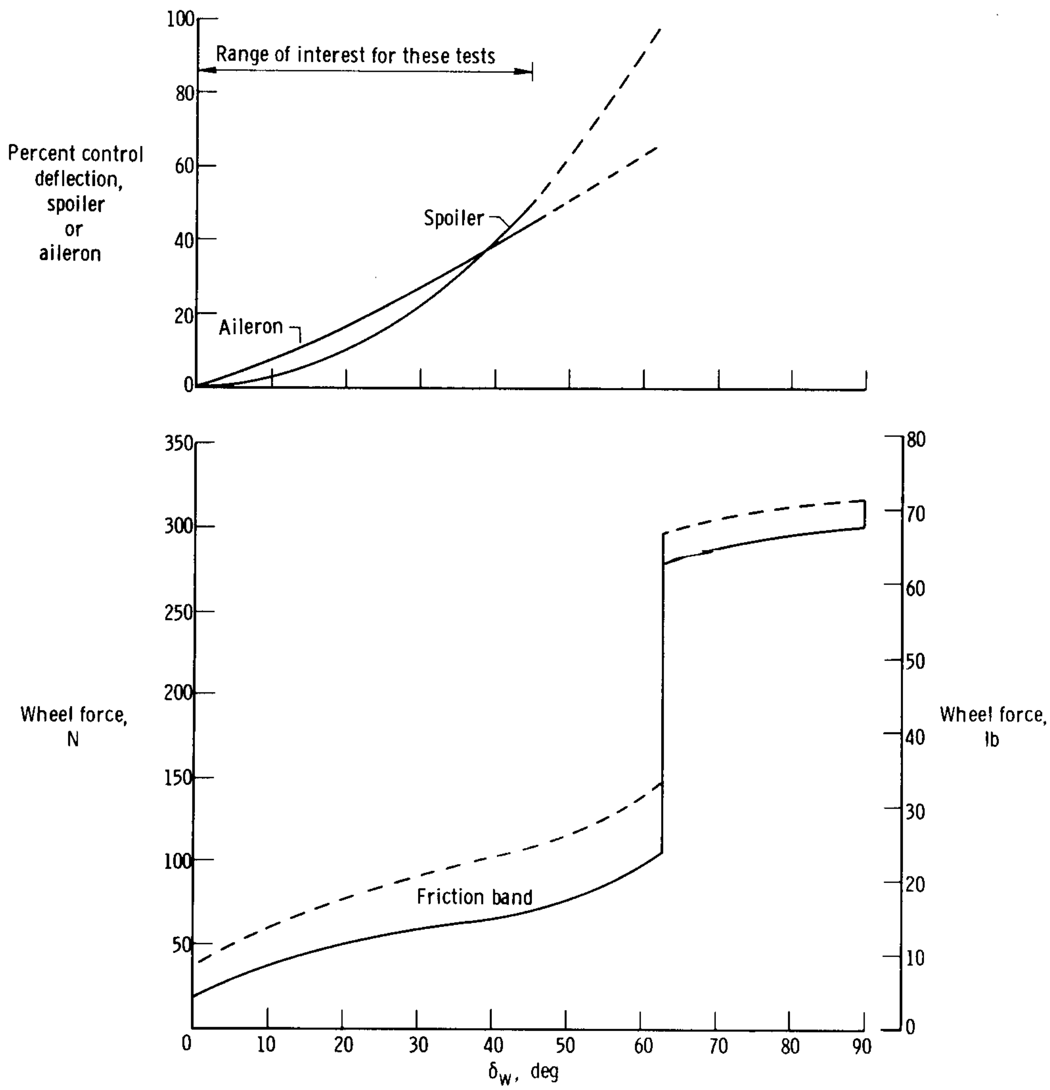



*Figure 3. Pilot's wheel force deflection characteristics for roll control.*

A 30-percent-chord rudder provided directional control and was actuated either hydraulically or manually through conventional rudder pedals. For manual control a one-to-one control-tab-to-rudder deflection and a trim tab were provided. Maximum available rudder deflection was limited to ±25° and to the hinge-moment capability of the dual hydraulic system. If complete failure of the dual hydraulic system had occurred, there was automatic reversion to manual aerodynamic control. Rudder pedal force was a function of aerodynamic hinge moment and differential cable motion in the manual mode, and of the artificial feel system and spring and cable motion in the powered mode.

Longitudinal control was accomplished by moving the pilot's or copilot's control column forward or aft. The motion was transmitted to the flight tabs which provided aerodynamic boost to the elevator. Elevator auxiliary tabs provided antifloat compensation to keep the elevators faired to the stabilizers. Elevator travel limits were 25° up to 12° down from the streamline position. Flight tab limits were 12° up to 25° down from streamline. Elevator auxiliary tab travel was about 4° to 25° trailing edge down and was programed as a function of stabilizer position.

The horizontal tail was used for longitudinal trim by varying its angle of incidence. This control could be actuated hydraulically, electrically, and mechanically.

Two slotted Fowler flaps were installed on each side of the aileron on the trailing edge of the wing. The flap design provided high lift and low drag when the flaps were partially extended and high lift and high drag when fully extended. The flaps had five detents (up or 0°, and 10°, 27°, 36°, and 50°). Only the 50° detent was used in these tests. Eight leading-edge (Krueger) flaps were hinge-mounted to the underside of each wing at approximately the 2-percent-chord position. These flaps were either fully closed or fully extended and were used for takeoff and landing. They extended from 96° to 118°, with the deflection increasing from inboard to outboard. However, for the 50° Fowler flaps the inboard leading-edge-flap section was retracted to reduce buffet.

Pilot's controls. – Side-by-side conventional control wheels connected by a crossover tube provided roll control for the pilot and copilot. The pilot's wheel had a total rotational travel of ±90° and commanded full 20° of aileron flight tab deflection and, through the crossover tube, full spoiler deflection for a wheel rotation of 63° to 90° (fig. 3). The tests were conducted from the pilot's position with the wheel deflections restricted to either 15°, 30°, or 45°.

The rudder control system consisted of adjustable rudder pedals, a feel system, hydraulic control system, flight tab, and rudder. For normal operation rudder control was fully powered. Rudder feel was simulated by a "q" cylinder which varied resistance to rudder pedal movement to correspond to variations in airspeed. During manual operation, the artificial feel system was bypassed and aerodynamic action of the flight tab supplied force feel.

For longitudinal control the pilot's column was connected to the left-elevator flight tab and the copilot's column was connected to the right-elevator flight tab. The columns were interconnected by two spring-loaded crossover tubes. Bob weights and balance springs were installed at the base of each pilot's column to provide desirable stick forces during turns. Elevator down springs provided stick-free stability. The down springs provided a restoring stick force exceeding the control system friction whenever the airplane speed was at least 10 percent below or above the trim speed. The down springs exerted the greatest force with the airplane in the clean configuration. The force was decreased as the wing flaps were lowered.

## Test Maneuvers

Pilot evaluation of the lateral handling of the test airplane during simulated and actual correction for lateral offsets was made in the final approach configuration (leading- and trailing-edge flaps and landing gear fully extended) without yaw damper augmentation. Evaluations at an altitude of approximately 3048 meters (10,000 feet) were made at indicated airspeeds of approximately 140 knots and 180 knots. The higher airspeed was selected as the highest allowable for the configuration and provided a slightly wider range of roll response data to be evaluated. The simulated sidestep maneuvers were flown at altitude, and, if the pilot was satisfied with the controllability of the airplane, he made actual offset approaches to landings at approximately the approach reference velocity and 180 knots. The simulated instrument-landing approaches were flown with a lateral offset to the runway of 61 meters (200 feet). At an altitude of 61 meters (200 feet) the pilot "became visual," corrected to aline with the runway, and performed the landing. Pilot comments and ratings based on the Cooper-Harper scale (ref. 8) were recorded after the maneuvers and landings (table 2) were evaluated.

TABLE 2. – SUMMARY OF TEST CONDITIONS AND PILOT RATINGS

| Pilot | Pilot rating | Airplane weight, kg (lb) | $V_i$, knots | h, m (ft) | $\delta_w$ limit, deg |
|---|---|---|---|---|---|
| A | 2 | 70,800 (156,000) | 180 | 3048 (10,000) | 45 |
| | 3 | 70,800 (156,000) | 180 | 3048 (10,000) | 30 |
| | 2.5 | 70,550 (155,500) | 135 | 3048 (10,000) | 45 |
| | 5 | 70,550 (155,500) | 135 | 3048 (10,000) | 30 |
| | 7 | 70,550 (155,500) | 135 | 3048 (10,000) | 15 |
| | 2 | 68,600 (151,100) | 135 | Approach | 45 |
| | 4 | 67,550 (148,900) | 135 | Approach | 30 |
| | 8.5 | 67,000 (147,600) | 135 | Approach | 15 |
| | 2 | 65,550 (144,500) | 180 | Approach | 45 |
| | 4 | 64,600 (142,500) | 180 | Approach | 30 |
| | 7.5 | 64,200 (141,500) | 180 | Approach | 15 |
| B | 2 | 71,200 (157,500) | 180 | 3048 (10,000) | 45 |
| | 3.5 | 70,800 (156,000) | 180 | 3048 (10,000) | 30 |
| | 6.5 | 70,200 (154,700) | 180 | 3048 (10,000) | 15 |
| | 2 | 69,200 (152,500) | 134 | 3048 (10,000) | 45 |
| | 4.5 | 69,200 (152,500) | 134 | 3048 (10,000) | 30 |
| | 8 | 68,750 (151,500) | 134 | 3048 (10,000) | 15 |
| | 2 | 64,850 (143,000) | 180 | Approach | 45 |
| | 2.5 | 64,400 (142,000) | 180 | Approach | 30 |
| | 8 | 63,500 (140,000) | 180 | Approach | 15 |
| | 2 | 62,800 (138,400) | 134 | Approach | 45 |
| | 6.5 | 62,150 (137,000) | 134 | Approach | 30 |
| | 8.0 | 61,700 (136,000) | 134 | Approach | 15 |
| C | 1.5 to 2.0 | 69,200 (152,500) | 180 | 3048 (10,000) | 45 |
| | 2.5 to 3.0 | 67,600 (149,000) | 180 | 3048 (10,000) | 30 |
| | 7 | 67,150 (148,000) | 180 | 3048 (10,000) | 15 |
| | 3 | 66,450 (146,500) | 140 | 3048 (10,000) | 45 |
| | 4.0 to 4.5 | 66,000 (145,500) | 140 | 3048 (10,000) | 30 |
| | 8 | 65,550 (144,500) | 140 | 3048 (10,000) | 15 |
| | 2 | 65,100 (143,500) | 180 | Approach | 45 |
| | 4 | 62,850 (138,500) | 180 | Approach | 30 |
| | 8 | 62,550 (137,800) | 180 | Approach | 15 |
| | 2.5 | 61,400 (135,400) | 140 | Approach | 45 |
| | 4.5 | 60,550 (133,500) | 140 | Approach | 30 |
| | 8 | 59,900 (132,000) | 140 | Approach | 15 |
| D | 2.0 to 3.0 | 88,900 (196,000) | 180 | 2650 (8700) | 45 |
| | 2.0 to 3.0 | 88,400 (195,000) | 180 | 2620 (8600) | 30 |
| | 8.0 to 9.0 | 88,000 (194,000) | 180 | 2288 (7500) | 15 |
| | 2.0 to 3.0 | 88,000 (194,000) | 152 | 2440 to 3048 (8000 to 10,000) | 45 |
| | 4 | 87,800 (193,600) | 152 | 2440 to 3048 (8000 to 10,000) | 30 |
| | 8 | 87,050 (192,000) | 152 | 2440 to 3048 (8000 to 10,000) | 15 |
| | 5 | 86,300 (190,300) | 180 | Approach | 30 |
| | 7 | 84,800 (187,000) | 152 | Approach | 30 |
| | 7 | 84,000 (185,300) | 151 | Approach | 30 |

For the instrument approach, the pilot used the conventional displays of the test airplane with the instrument-landing-system crosspointer.

The pilot's cockpit control positions, airplane aerodynamic control positions, angular rates, and center-of-gravity linear accelerations were recorded on standard internally recording oscillographs. The records were synchronized by a common timer. Airplane fuel and location of fuel were recorded by the flight engineer during the flight. Airspeed and altitude data were also recorded on the oscillographs.

## RESULTS AND DISCUSSION

### Pilot Evaluations at Altitude

Four pilots evaluated the roll characteristics of the test airplane at altitude by making simulated lateral-offset corrections to an assumed runway and other maneuvers as desired with three levels of roll control wheel capability.

The results of these pilot evaluations are summarized in figure 4. A roll acceleration of 10 deg/sec$^2$ was required for a pilot rating of satisfactory and a value of less than 4 deg/sec$^2$ was rated unacceptable. All pilot evaluations were in good agreement, with most ratings being within one-half rating number of the mean pilot rating. The pilot rating results are tabulated in table 2, and comments are summarized in the next section.

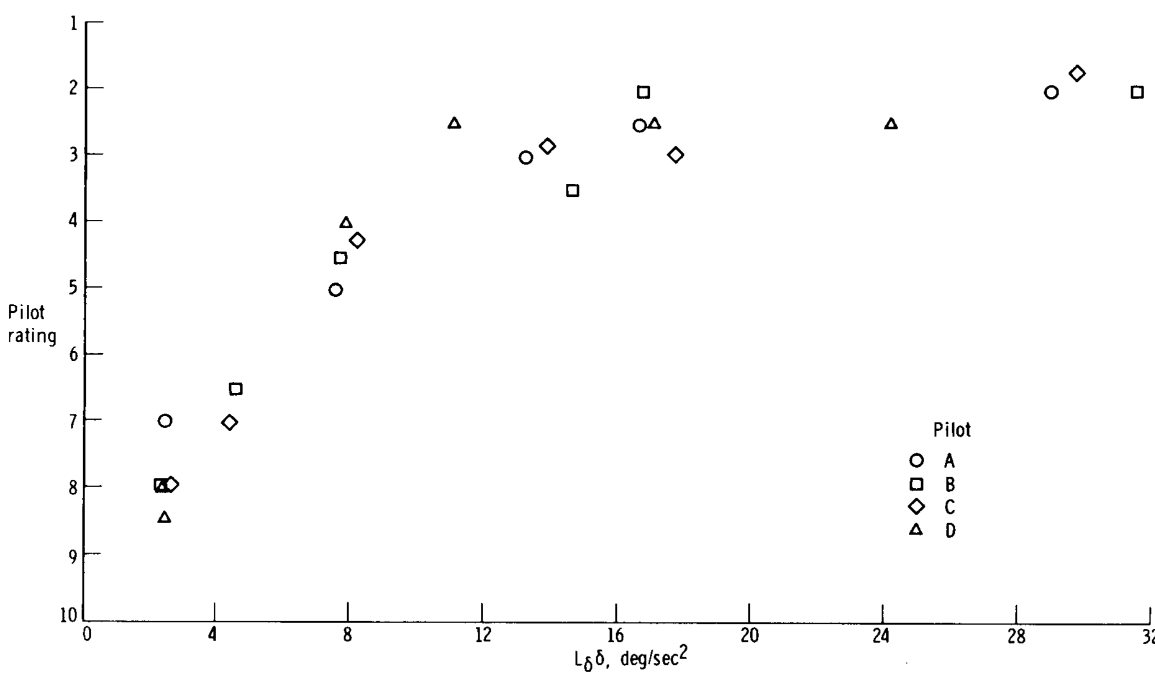



*Figure 4. Pilot evaluation of the roll control at 3048 meters (10,000 feet). Landing configuration.*

### Summary of Pilot Comments Concerning the Roll Control Evaluations at Altitude

$L_\delta\delta \approx 30$ deg/sec$^2$. — In roll maneuvers that simulated corrections for an offset during approach with $L_\delta\delta \approx 30$ deg/sec$^2$, the wheel stop was not hit and the roll rate was satisfactory. With the roll control available, the roll response was definitely good enough for any offset maneuvering during approach. Roll control available seemed to be in excess of that required during approach. Dutch roll characteristics limited the lateral control pilot rating to 2, but lateral control power was adequate. As indicated in table 2, the average of the pilot ratings for this condition was about 2.0.

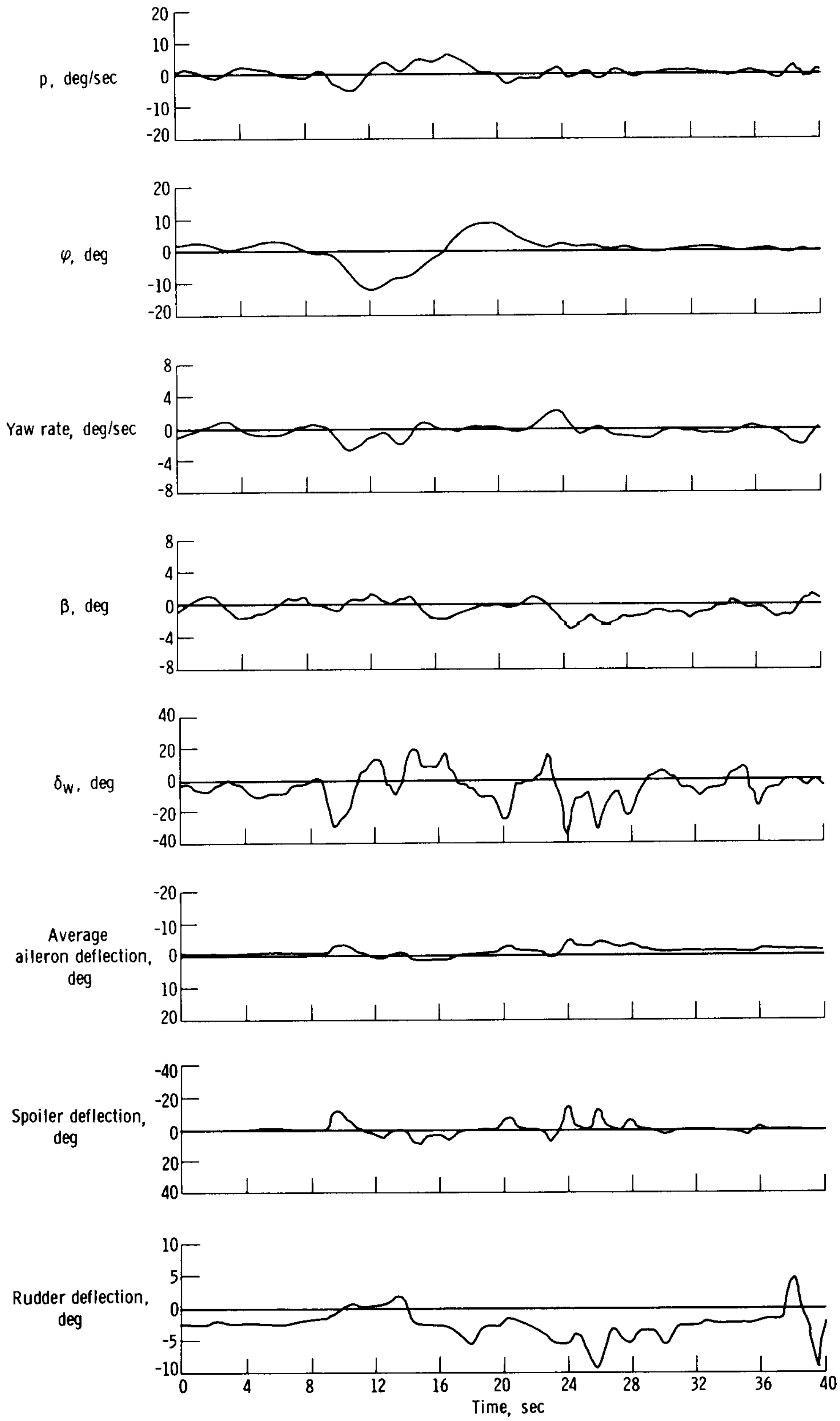
$L_\delta\delta \approx 12$ to 18 deg/sec$^2$. — The range of roll rate capability from 12 to 18 deg/sec$^2$ was satisfactory. It was approximately the range that was used during the simulated offset maneuver. The control was limited several times during recovery from an offset approach. All the control available was used occasionally. This control power for a precise approach with "reasonable" winds and without gusts would be adequate. More severe crosswinds and gusty conditions might require more control power than was available, but the lateral-control power available was adequate and was no more than required for normal approach maneuvering. The average pilot rating was 3.0.

$L_\delta\delta \approx 7$ to 8 deg/sec$^2$. — The control power available at $L_\delta\delta \approx 7$ to 8 deg/sec$^2$ was adequate but not satisfactory. More roll capability was desired. Roll control for mild instrument-landing maneuvering might be adequate, but moderately rapid wings-leveling maneuvers that might be necessary because of turbulence would require higher control power. The pilot must wait for roll rate to develop and bank angle to change. The offset maneuver can be performed; however, more aileron response would be preferred. The average pilot rating was 4.5.

$L_\delta\delta \approx 2$ to 4 deg/sec$^2$. — Actually, for $L_\delta\delta \approx 2$ to 4 deg/sec$^2$ more control power was required just for normal visual-flight maneuvering. Full control resulted in very slow response initially, and it never increased. This level of control power was considered to be unsatisfactory for correcting for an offset during approach. There was positive roll, but after the initiation of the control input, there was a delay in roll response. Roll response was so low that normal deviations during instrument-landing-system approaches could not be corrected as rapidly as desired. The offset maneuver could not be safely accomplished even in smooth air with normal piloting techniques. The average pilot rating was 7.5.

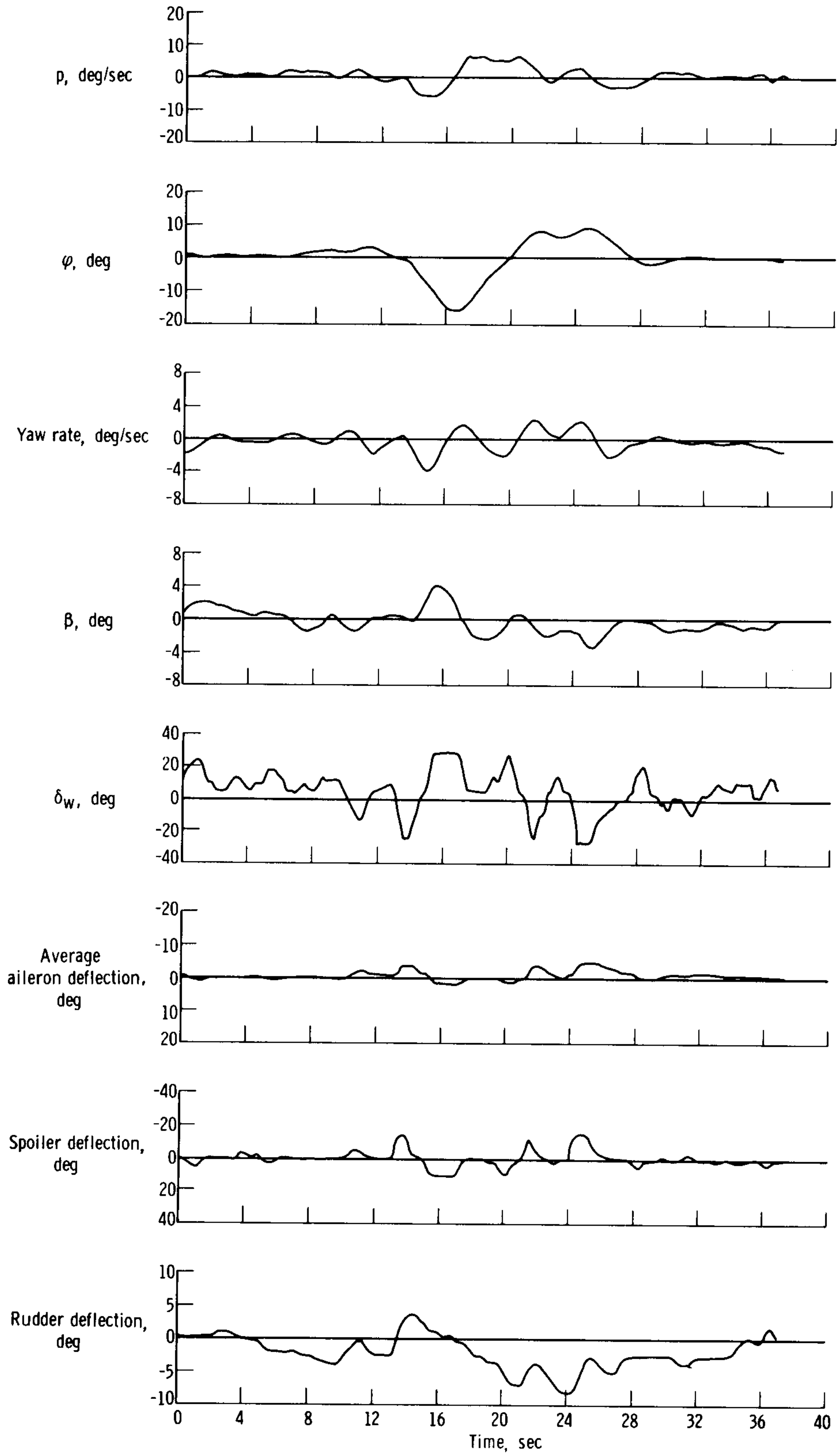
### Pilot Evaluations During Offset Approaches

After experience at altitude, roll-response characteristics were evaluated during offset approaches to a landing. Actual approaches and landings were made at each flight condition and level of roll control power selected. The results are summarized in table 2. Time histories of offset approaches to landings by pilot A are presented in figure 5. With the wheel rotation restricted to 45° of deflection (figs. 5(a) and 5(d)), a rotation of 45° was never commanded by the pilot. This condition was synonymous with unrestricted controls. The roll capability was rated as 2 to 2.5, satisfactory. With the wheel restricted to 30° (figs. 5(b) and 5(e)), several instances occurred when the pilot would have commanded control authority beyond the limit. The pilot indicated



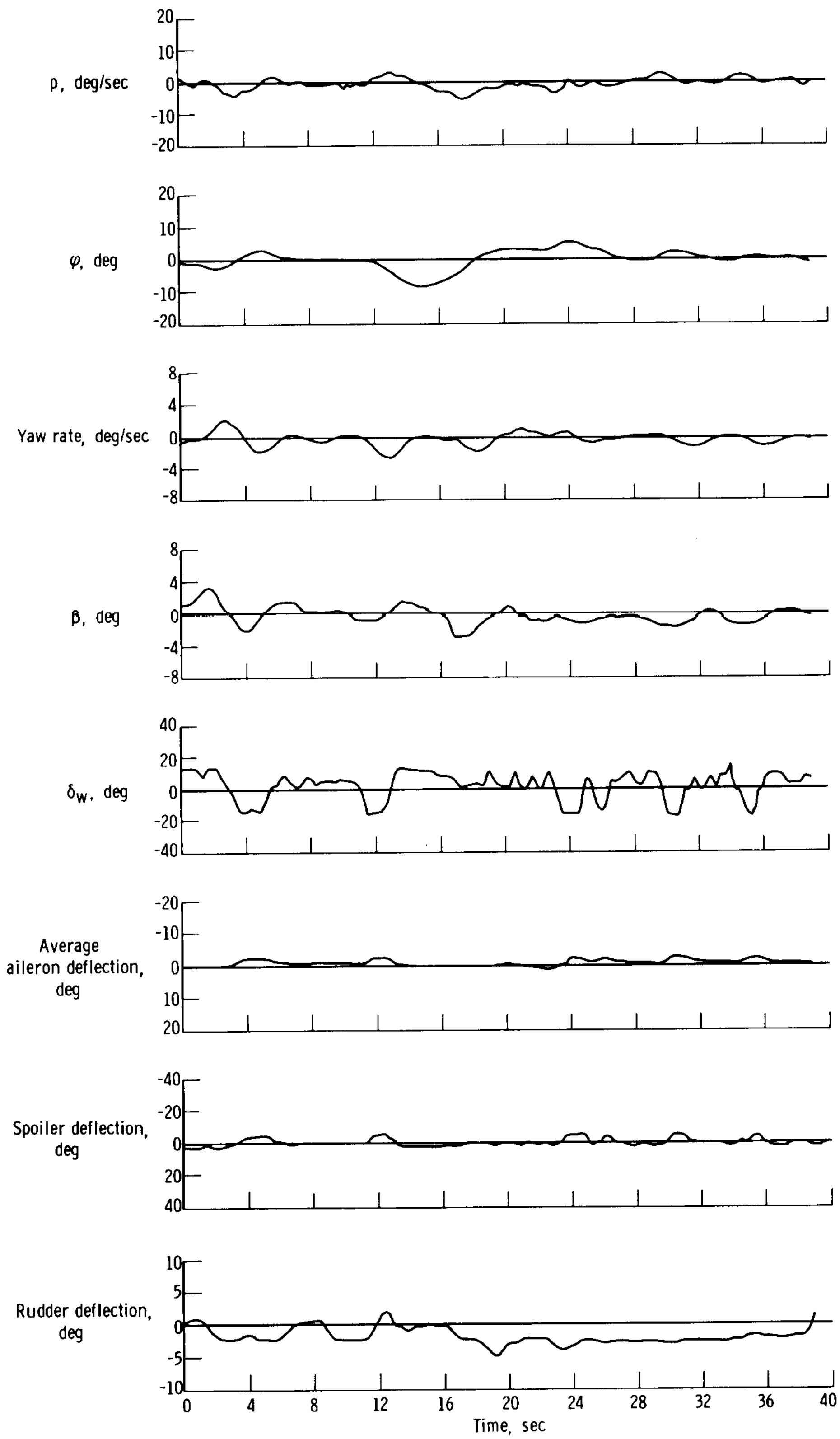

*(a) 180 knots;* $\delta_W = 45^o$.

*Figure 5. Lateral-offset approaches to a landing by pilot A.*



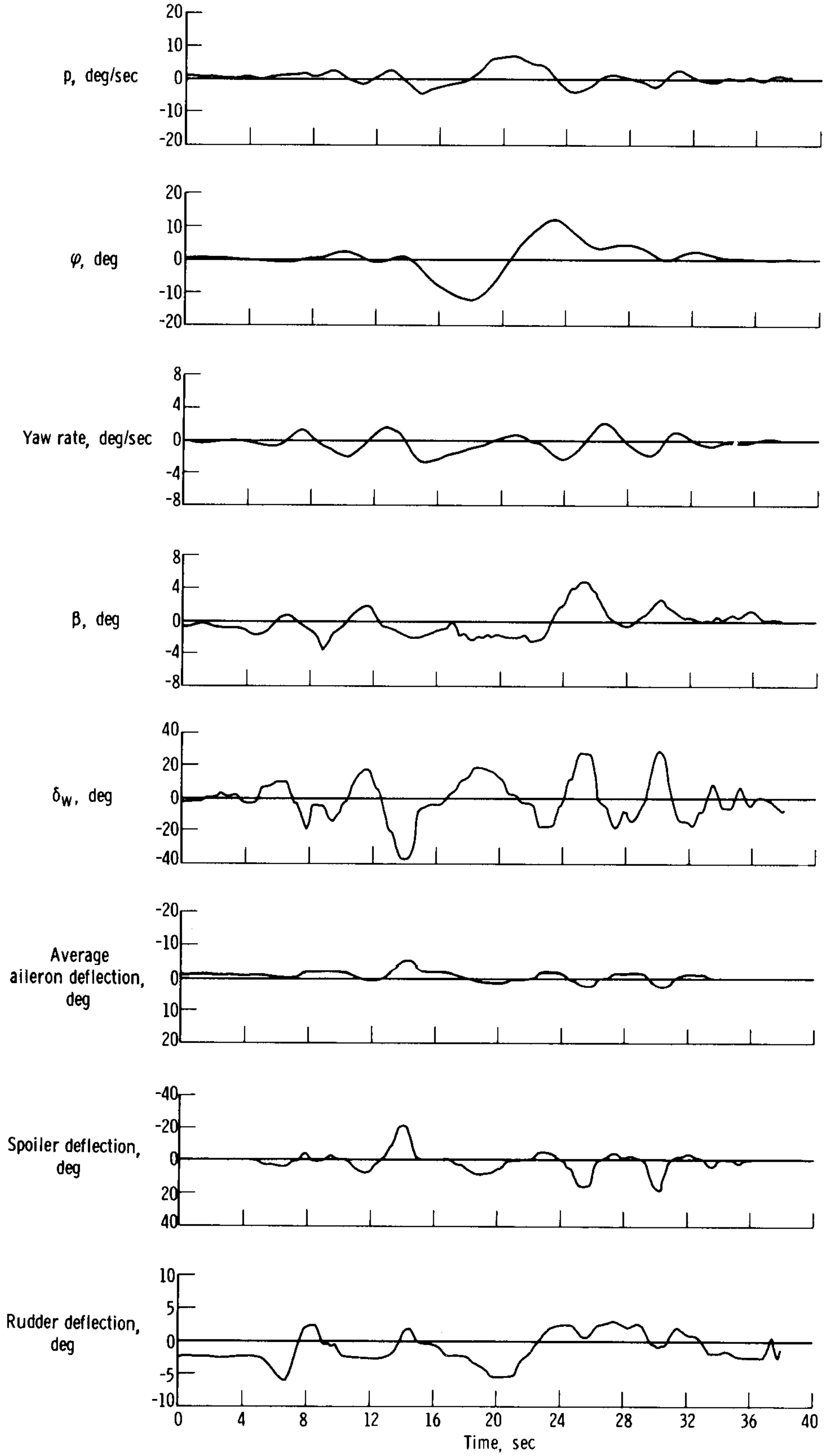

*(b) 180 knots; $\delta_w = 30^o$.*

*Figure 5. Continued.*



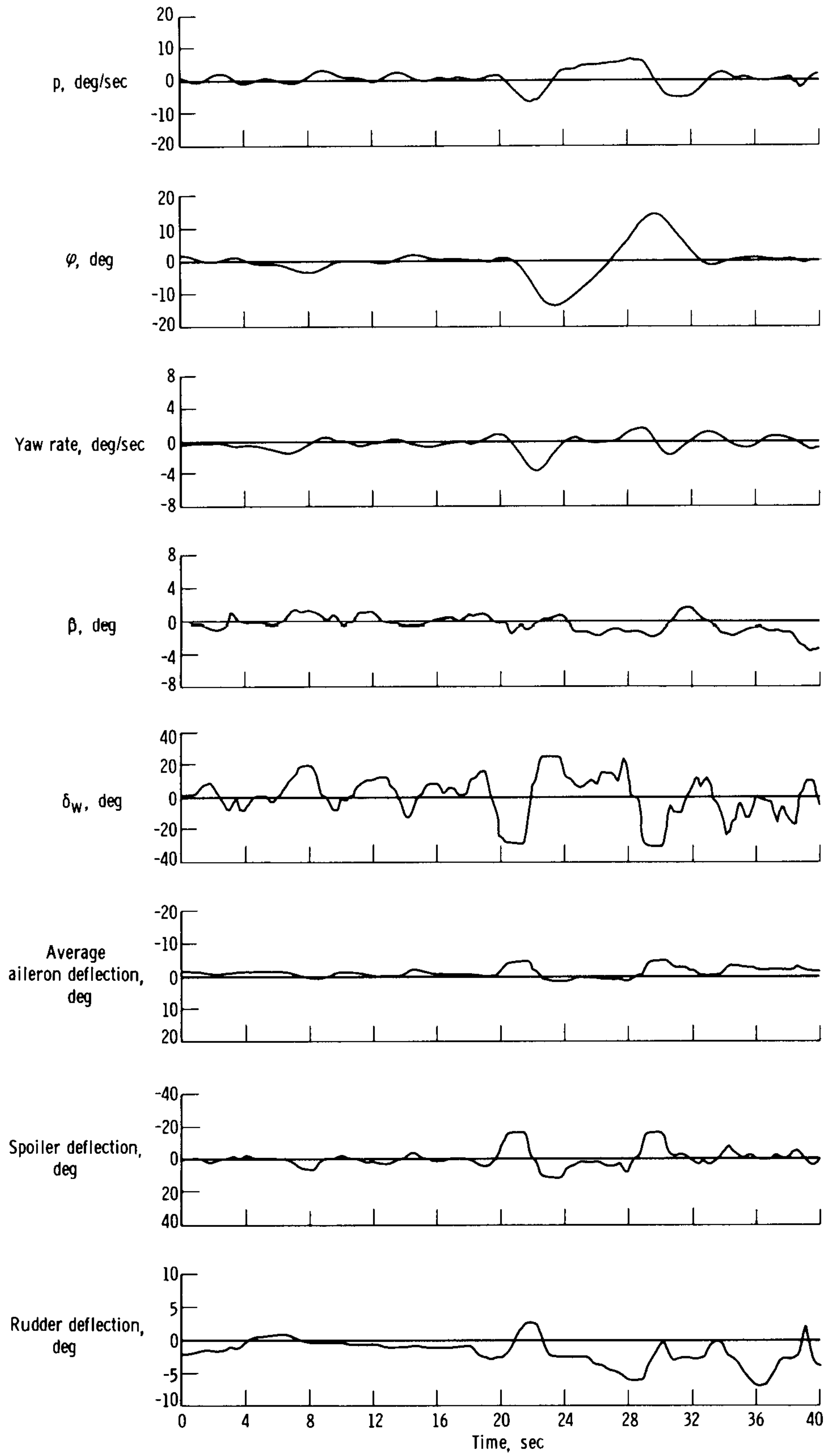

*(c) 180 knots; $\delta_w = 15^o$.*

*Figure 5. Continued.*



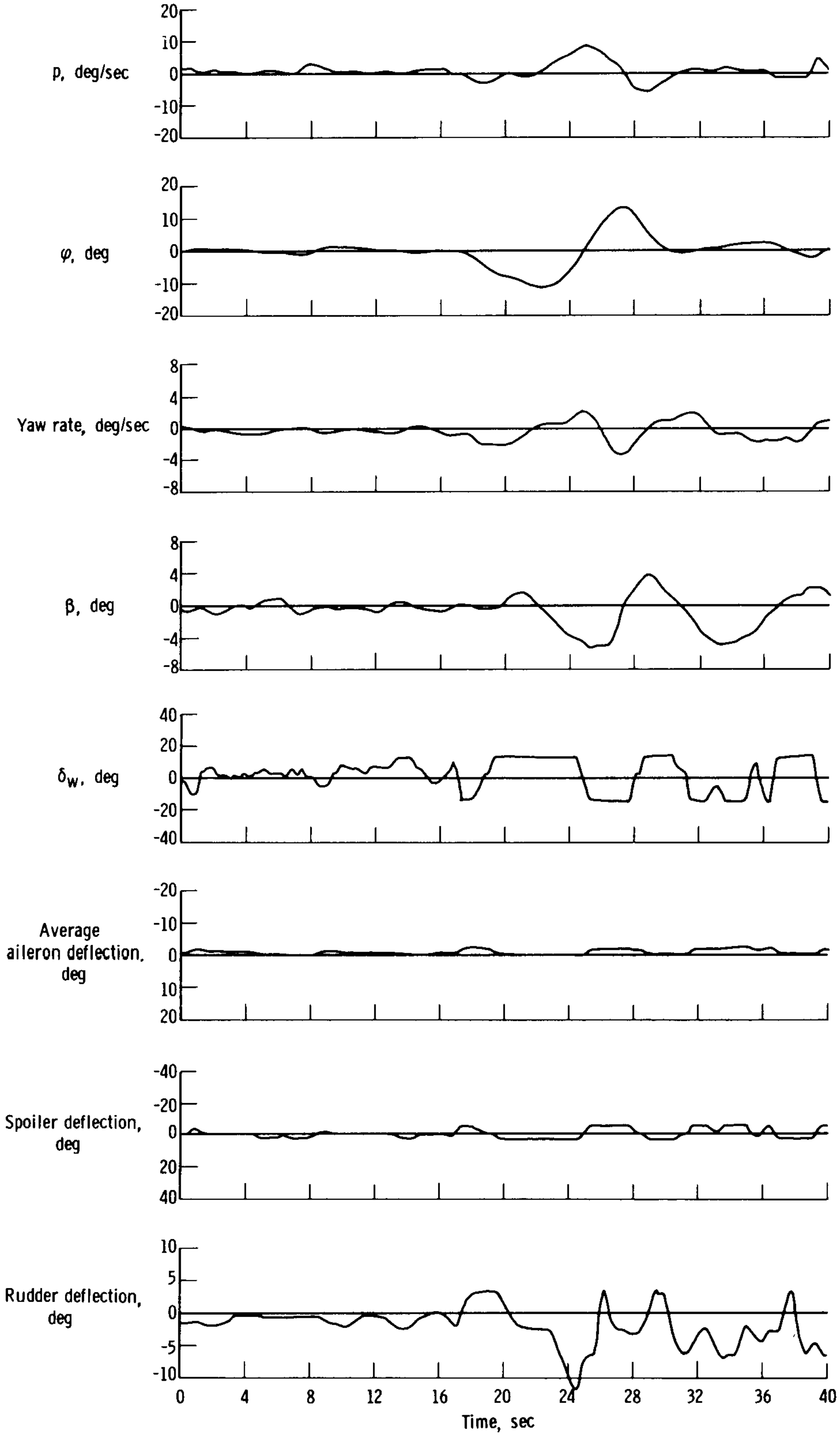

*(d) 135 knots;* $\delta_w = 45^o$.

*Figure 5. Continued.*




*(e) 135 knots; $\delta_W = 30^o$.*

*Figure 5. Continued.*




*(f) 135 knots; $\delta_w = 15^o$.*

*Figure 5. Concluded.*

that controllability was slightly degraded. He rated the controllability as 4.

In controlling with the wheel restricted to only 15° of rotation (figs. 5(c) and 5(f)), the pilot commanded as much control as was allowed a high percentage of the time. The pilot accomplished the desired landings; however, the controllability was rated 7.5 to 8.5, unacceptable. One pilot chose not to land with the 15° control wheel restriction. He thought that the airplane might become uncontrollable during some part of the maneuver with normal piloting techniques. The other pilots made the landings but were forced to alter their piloting technique slightly by not reducing power as early as they normally did or by using the rudder to augment the roll control. Detailed pilot comments are summarized in a later section and in appendixes A and B.

The pilot rating data for the lateral-offset approaches and landings are summarized in figure 6. Pilot ratings for a roll control capability of 15 deg/sec$^2$ or greater were similar whether in up-and-away flight or on an actual approach; the pilot rating was approximately 2.0. With the reduction in roll power during the approaches, the pilot ratings of controllability became higher (less satisfactory). A level of roll control power was rated less satisfactory for actual approaches than for evaluations at altitude. (Compare figs. 4 and 6.) The actual approach provided the realism required for the approach task evaluation. Thus it appears that it is necessary to perform actual approaches to obtain meaningful pilot evaluations of the roll requirements for approach.

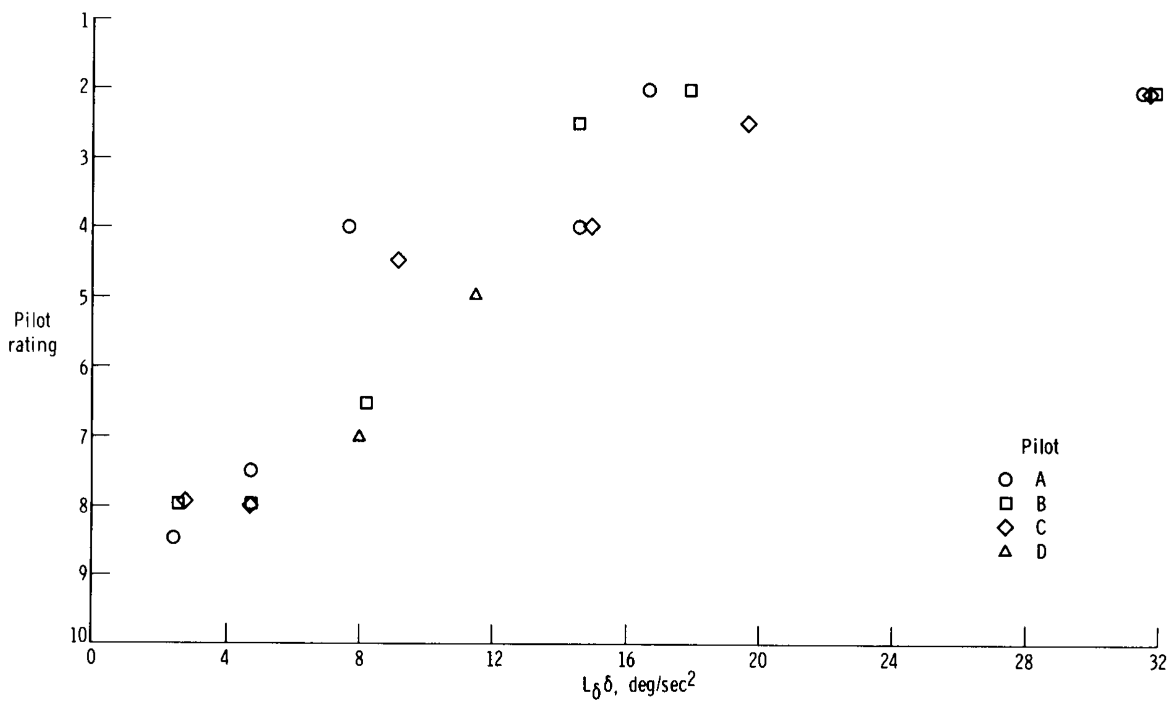



*Figure 6. Pilot evaluation of roll control during actual approaches to landing. Pilot D did not attempt to land with* $\delta_w = \pm 15^o$.

Although the interpilot rating data are in good agreement at each end of the pilot rating scale, there was more spread in pilot rating in the midrange of the roll control power investigated; the pilot ratings ranged from 4 to 7. All the evaluation pilots were test pilots with varied backgrounds of flying. There appeared to be a wide variance in pilot opinions of the level of roll control power required for acceptable but unsatisfactory control. Because the sampling of evaluations was very small, only one per pilot, circumstances peculiar to that evaluation would greatly influence the variability of the data. For example, slightly increased turbulence during the maneuver would affect the rating. These effects may be noted in the detailed pilot comments, in which it appears that a slight increase in turbulence or difference in piloting technique, or both, caused two of the pilots to command all the roll control that was available, whereas the other two pilots were able to complete the landings without commanding the maximum control available. Their ratings were therefore more similar to the ratings for the higher control effectiveness and were lower (more satisfactory ratings).

Evaluations were requested at 140 knots and 180 knots, but they were made at the reference velocity, which was a function of airplane weight, and at 180 knots; however, no effect of the approach velocity other than the effect of dynamic pressure was noted during the tests.

### Summary of Pilot Comments Concerning the Actual Offset Approaches to Landings

$L_\delta\delta \approx 32$ to 18 deg/sec$^2$. – From the lateral control standpoint, the range of control power of $L_\delta\delta \approx 32$ to 18 deg/sec$^2$ was very good. More roll control power was available than was commanded by the pilots. The offset correction was made with sufficient control power. In fact, the time required for the sidestep maneuver could have been reduced safely. Control response was good. There was enough control power to complete the maneuver satisfactorily. The average pilot rating was 2.0.

$L_\delta\delta \approx 15$ deg/sec$^2$. – During final approach with an $L_\delta\delta \approx 15$ deg/sec$^2$, there was no tendency to command control beyond the control limits. Occasionally during the offset corrections, more control was requested than was available. The rolling capability and ability to return to the runway centerline was barely satisfactory. On one occasion some rudder was used to obtain the roll desired. However, one pilot did not command more roll control than was available and so was not restricted in the control commanded. The maneuver was in smooth air and he believed the airplane response and control was satisfactory because no more control power was commanded than was available. The average pilot rating was 3.5.

$L_\delta\delta \approx 8$ deg/sec$^2$. – Satisfactory bank angle was obtained for the correction to the runway centerline with an $L_\delta\delta \approx 8$ deg/sec$^2$; however, more control power was desired to roll out at the runway centerline. One pilot indicated that he was afraid to bank too much so he traveled farther down the runway in order to reach the centerline for touchdown. A second pilot commented that he considered having to wait for response in roll to be extremely poor control. The offset maneuvers could be and were completed. All the control available was used. The pilots believed that this level of control was the limit for the maneuver. The average pilot rating was 5.5.

$L_\delta\delta \approx 2$ to 5 deg/sec$^2$. – For a control power level of $L_\delta\delta \approx 2$ to 5 deg/sec$^2$, more control was desired than was available during the instrument-landing-system approach. By allowing only very conservative bank angles of approximately 15°, the pilot was able to correct back to the centerline of the runway. He accepted a touchdown point farther down the runway to allow time to correct the offset. Much bank angle anticipation was required. The required maneuver was beyond the limit of the lateral control available. Some rudder was used to augment the very low roll control power. The roll control power was completely unsatisfactory and was unsafe for normal corrections to the runway. The average pilot rating was 8.

## Comparisons of Roll Data With Referenced Results

The lateral-directional stability and control characteristics for the approach configuration (table 3) were measured during another part of the program. With the aerodynamic characteristics of the airplane and the roll control system characteristics (control system lag was approximately 0.4 sec), the airplane roll response could be converted to other parameters that have been used for correlating airplane handling qualities. The results of related studies as well as proposed roll criteria are compared with these results.

TABLE 3.—CV-990 CHARACTERISTICS IN LANDING APPROACH CONFIGURATION
[Landing gear down; flaps deflected 50°]

| | 140 knots | 180 knots |
|---|---|---|
| $L_p$, 1/sec | -0.838 | -0.899 |
| $L_r$, 1/sec | .325 | .280 |
| $L_\beta$, 1/sec$^2$ | -2.063 | -2.311 |
| $L_{\delta_a}$, 1/sec$^2$ | .235 | .401 |
| $L_{\delta_r}$, 1/sec$^2$ | .210 | .188 |
| $L_{\delta_s}$, 1/sec$^2$ | .509 | .694 |
| $N_p$, 1/sec | -.087 | -.067 |
| $N_r$, 1/sec | -.116 | -.152 |
| $N_\beta$, 1/sec$^2$ | .522 | .839 |
| $N_{\delta_a}$, 1/sec$^2$ | .0546 | .0689 |
| $N_{\delta_r}$, 1/sec$^2$ | -.424 | -.597 |
| $N_{\delta_s}$, 1/sec$^2$ | .1134 | .154 |
| $Y_\beta$, 1/sec | -.146 | -.151 |
| $Y_{\delta_a}$, 1/sec | -.011 | .0011 |
| $Y_{\delta_r}$, 1/sec | .022 | .023 |
| $Y_{\delta_s}$, 1/sec | -.0006 | -.0046 |
| Test altitude, m (ft) | 3960 (13,000) | 3736 (12,260) |
| Gross weight, kg (lb) | 64,400 (142,000) | 73,950 (163,000) |
| $I_X$ (estimated), kg-m$^2$ (slug-ft$^2$) | 241,200 (178,000) | 258,800 (191,000) |
| $I_Z$ (estimated), kg-m$^2$ (slug-ft$^2$) | 7,520,000 (5,550,000) | 7,535,000 (5,560,000) |
| $\omega_d$, rad/sec | .914 | 1.0235 |
| $\zeta_d$ | .0353 | .0567 |
| $\tau_R$, sec | .969 | .928 |
| $\omega_\varphi/\omega_d$ | 1.094 | 1.139 |
| $\varphi/\beta$ | 1.84 | 1.70 |

Figure 7 presents the bank angle achieved in 2 seconds for the levels of roll control power investigated with pilot rating as a parameter. Approximately 12° of bank angle change in 2 seconds were required for a pilot rating of satisfactory. The roll response less than about 6° in 2 seconds was unacceptable. The results show a much lower response to be satisfactory than the 30° bank angle change in 2 seconds that was predicted in reference 4 to be satisfactory for up-and-away flight.

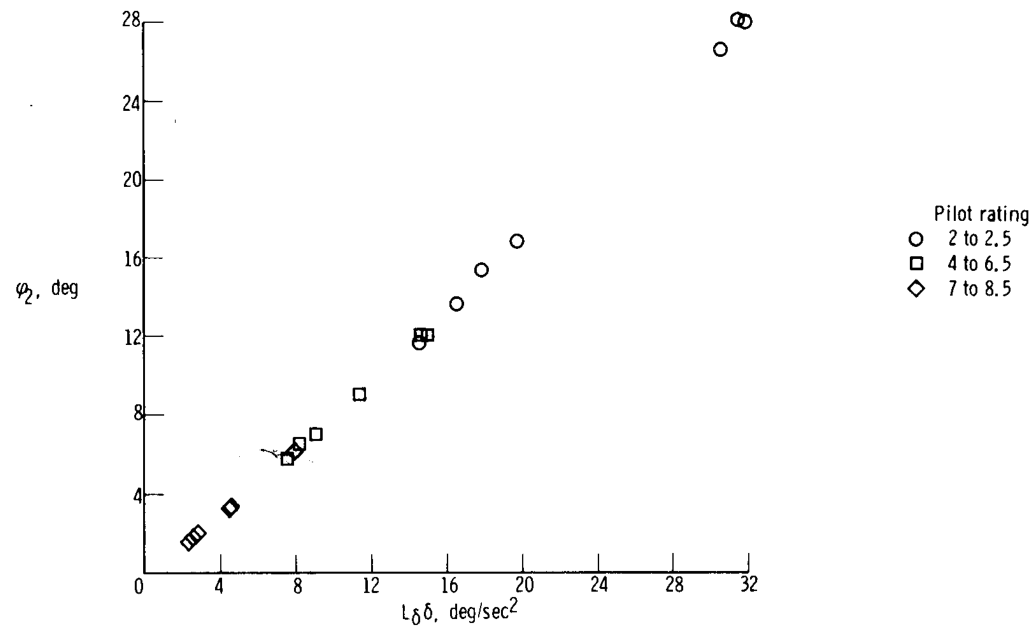



*Figure 7. Pilot evaluation in terms of bank capability in 2 seconds. Actual landing from offset approach.*

The time required to bank 30° (fig. 8) was compared with the Military Specification for piloted airplanes (ref. 5). For large transport airplanes in the landing approach

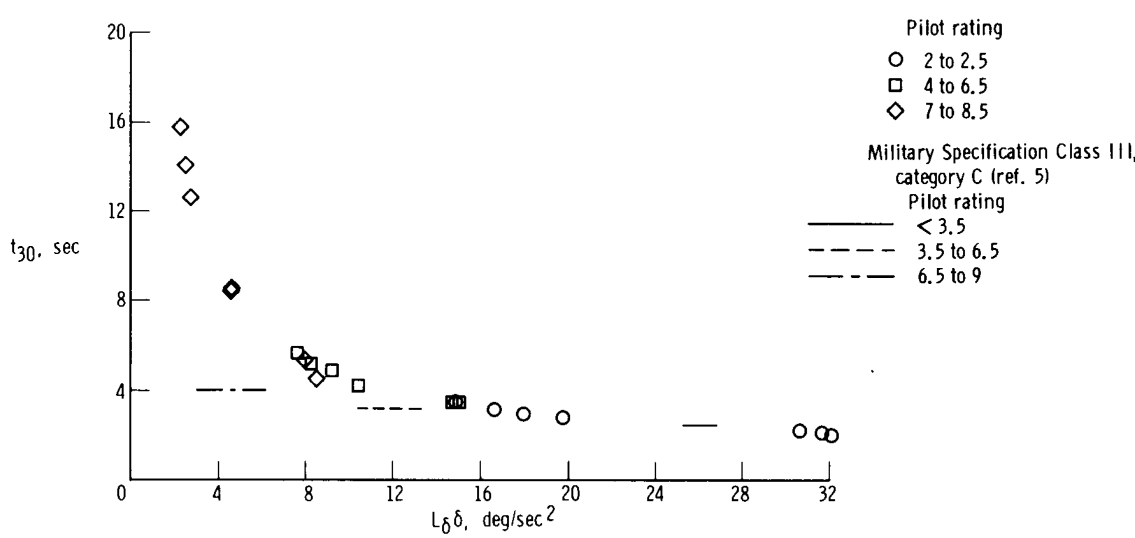
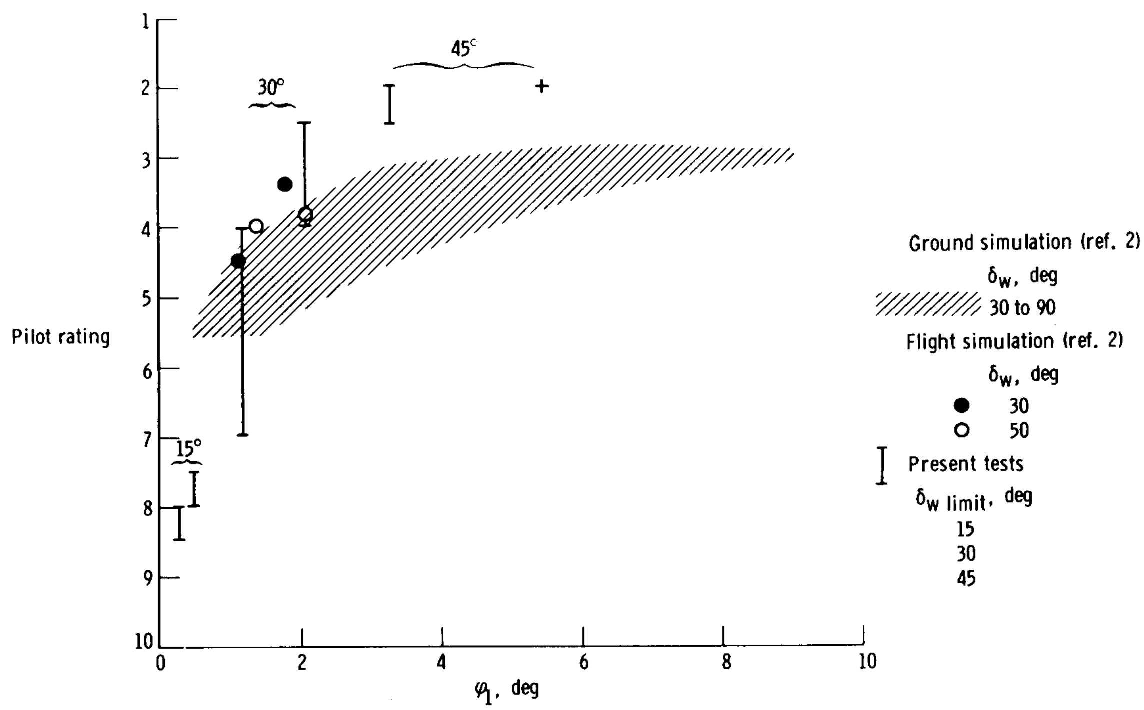



*Figure 8. Pilot evaluation in terms of time-to-bank 30° and comparison with reference 5. Actual landing from offset approach.*

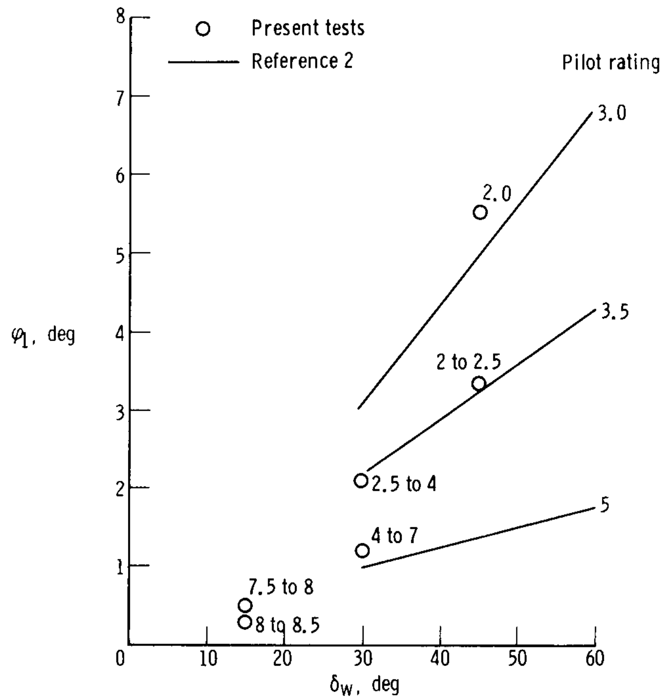
configuration, times to change the bank angle by 30° were specified to be 2.5, 3.2, and 4.0 seconds for flying qualities levels 1, 2, and 3, respectively, which correspond to pilot rating boundaries of 3.5, 6.5, and 9.0. The present data allow much more time to bank for the levels of flying qualities than given in the Military Specification (ref. 5). The results of this study imply that the Military Specification was conservative. Reference 4 indicated that 3 to 3.5 seconds would probably be considered to be satisfactory for the approach, which compares favorably with the present results.

Comparisons are also possible with the data of reference 2 (fig. 9). A range of control wheel deflection of 30° to 90°, which resulted in roll response in the first second of 1° to 9° bank angle change, was checked on a ground-based simulator (ref. 2). Two in-flight evaluations at control wheel deflections of 30° and 50° were made to verify the simulation data. Results are presented in terms of pilot rating versus bank angle change in the first second (fig. 9(a)) and bank angle change in 1 second versus control wheel deflection (fig. 9(b)). Inasmuch as there were some seemingly important differences in the mechanization of the two experiments, the present results are in generally good agreement with those of reference 2. In the study of reference 2 the control wheel gearing was changed and the maximum roll effectiveness was limited at various amounts of wheel throw. However, the pilot was allowed to continue to rotate the control wheel beyond the control limit, although no additional roll power was derived from the rotation. In the present tests control power was changed by limiting the maximum wheel throw of the pilot's control wheel, and the basic control system gearing was not changed. The pilots disliked the wheel limit at the $\delta_w = 15°$ and 30° limit deflections but could and did perform evaluations objectively.




*(a) Pilot rating versus bank angle change in 1 second.*

*Figure 9. Comparison of present evaluation results with in-flight and ground simulation results of reference 2.*




*(b) Bank angle change in 1 second versus control wheel deflection.*

*Figure 9. Concluded.*

Roll criteria. – The present data and the proposed roll criterion of reference 6 for transports during approach are compared in figure 10. These tests indicate that a lower roll rate than specified in reference 6 may be satisfactory. It also appears that

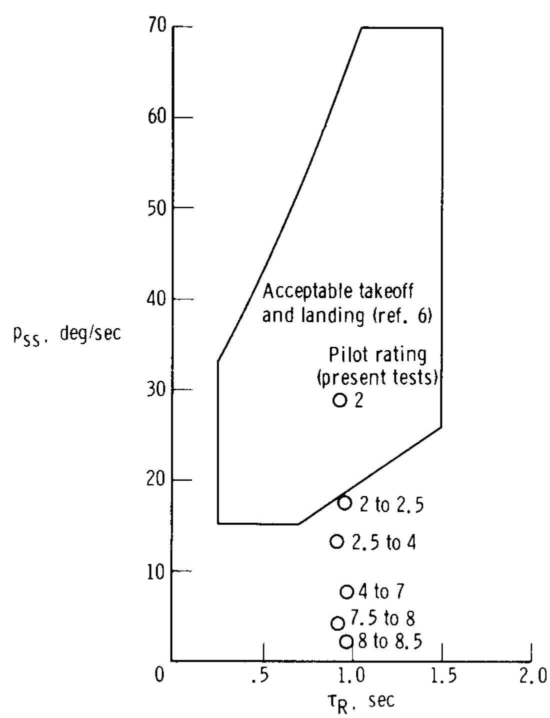



*Figure 10. Comparison of present evaluation results with the proposed criteria of reference 6.*

the suggestion in reference 4 of a minimum roll rate of 12 deg/sec for satisfactory pilot ratings may agree better with the present data than do the reference 6 results. The present data are also in somewhat better agreement with the criteria of reference 3 (fig. 11) than with the criterion of reference 6. Although the present data are limited, the agreement is consistent throughout the pilot rating range (2 to 8.5) and is considered to be good.

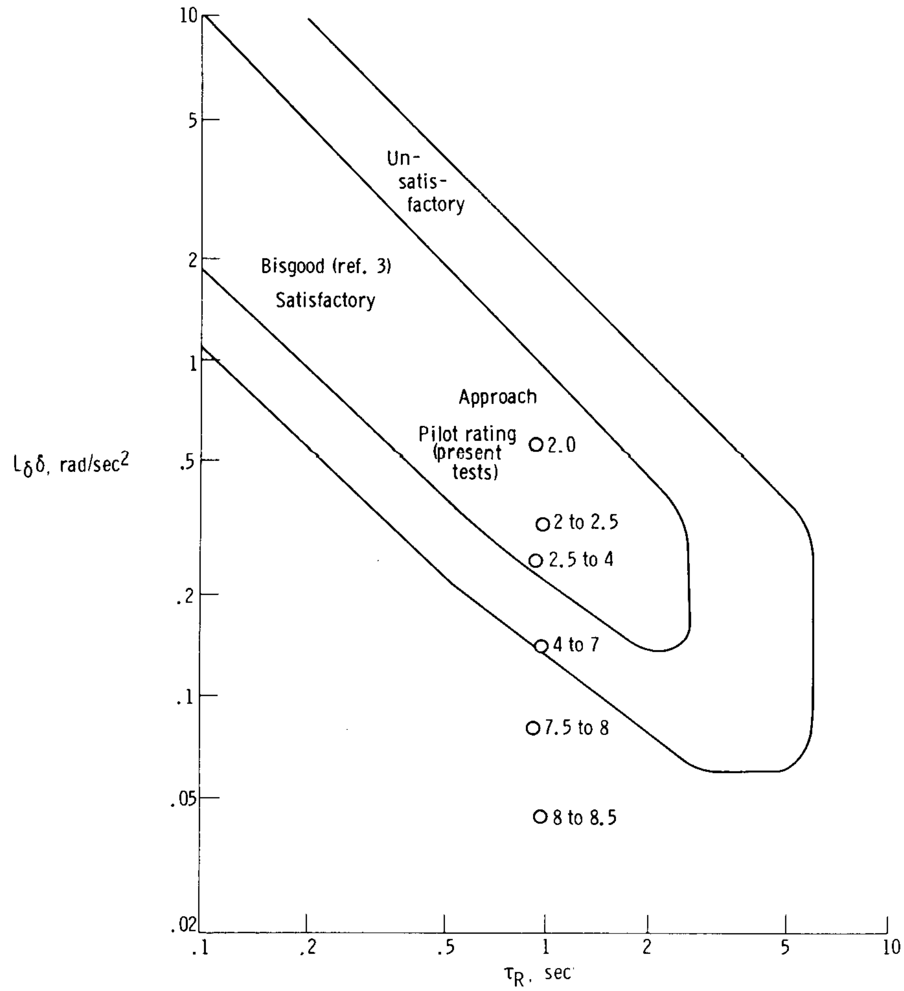



*Figure 11. Comparison of the present evaluation results and the proposed criteria of reference 3.*

Sidestep criteria. – Reference 9 considers the sidestep or lateral-offset maneuver to a landing and derives the time required to execute the maneuver as a function of bank angle. The derivation was based on the assumption that, ideally, the sidestep maneuver consists of sinusoidal variations of bank angle. Time was allowed to transition into and out of the bank angle. The derivation was for transports, and it was shown by flight test results that at normal approach speeds the distance required to perform the sidestep maneuver can be determined accurately. The data obtained from the present sidestep maneuvers are compared in figure 12 with the results of reference 9. Although there is wide variability in the experimental data, there is reasonable agreement between the experimental time required to complete the sidestep maneuver and the time calculated by the method of reference 9.

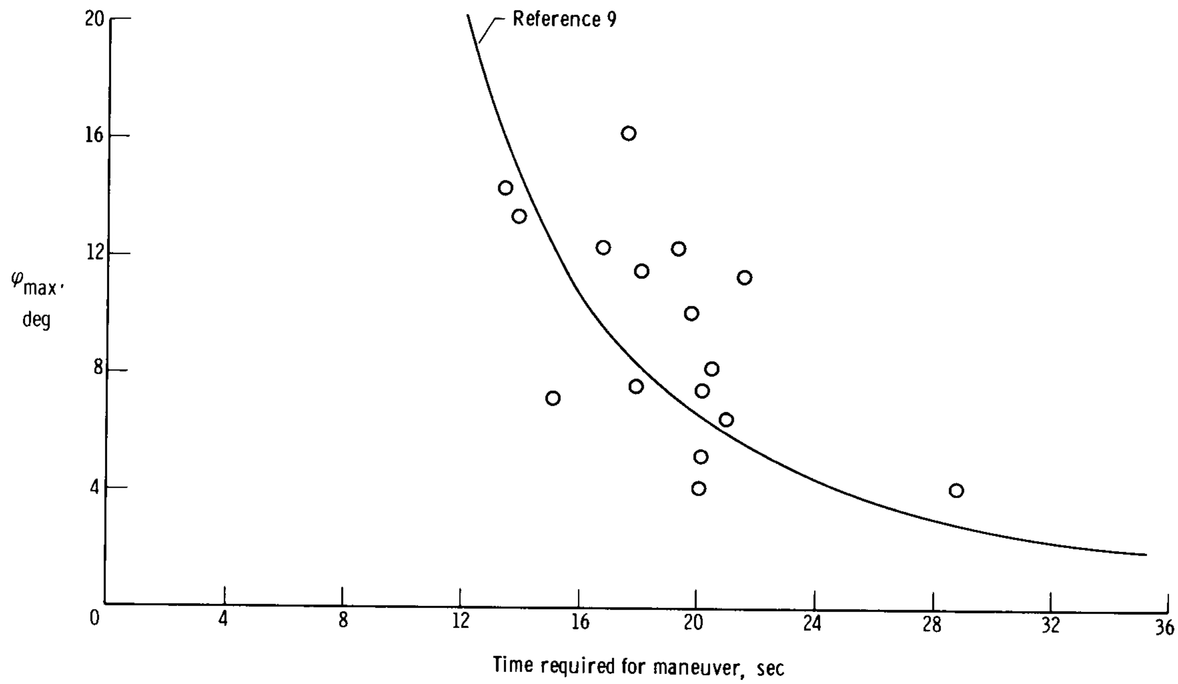



*Figure 12. Comparison of the time required for the sidestep maneuvers of the present tests and the lateral-offset-maneuver criterion of reference 9.*

## Pilot Rating Comparisons

Each pilot was requested to rate the controllability of each condition flown, first at altitude and then during actual approaches. As shown in figure 13, the pilot ratings

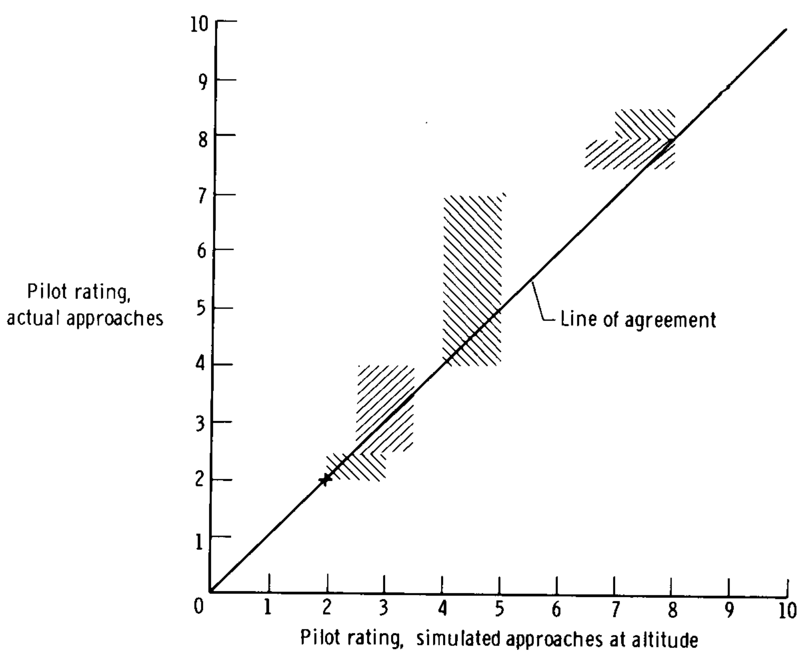



*Figure 13. Comparison of pilot evaluation during simulated offset maneuvers at altitude and actual offset approaches to a landing. Range of pilot ratings for each flight test condition shown by the cross hatching.*

at altitude and during actual approaches agree at the satisfactory end of the rating scale; however, the actual approaches were rated higher (poorer ratings) than the evaluations at altitude for all other levels of pilot rating. The actual approach to a landing was more demanding of the pilot than a simulated correction for a lateral offset at altitude. Average ratings differed by as much as a full rating number. Actual comments of two pilots are presented in appendixes A and B.

## CONCLUDING REMARKS

Pilot evaluations of the lateral control required for lateral-offset approaches to landings in a four-engine jet transport were made during flight at 3048 meters (10,000 feet) altitude and during actual approaches to landings in smooth air. Roll control power of about 15 $deg/sec^2$ was required for pilot ratings of satisfactory. Corrections for lateral offsets and landings could be made in smooth-air conditions with a very low level of control power, 2 $deg/sec^2$ to 5 $deg/sec^2$. However, the pilots used techniques that might not be operationally satisfactory for all approach situations, and the pilot ratings for the low roll capability were unacceptable (pilot rating of approximately 8).

The results of this study allow much more time to bank than required in the revised Military Specification for transports in the approach. The results were, however, in general agreement with several other studies of transport airplane roll response during approach.

The level of roll control power rated to be satisfactory during simulated approaches at altitude was rated satisfactory during actual landings. The level of roll control power rated to be unsatisfactory or unacceptable during simulated approaches at altitude was rated more unsatisfactory or unacceptable during actual approaches. Thus, it appears that it is necessary to perform actual approaches to obtain meaningful pilot evaluations of the roll requirements for approach.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., December 22, 1970.

## APPENDIX A

## TYPICAL PILOT COMMENTS ON ROLL EVALUATIONS AT ALTITUDE - PILOT B

### Simulated Approaches at 180 Knots

$\delta_W = 45°$. – The aileron control power in the approach configuration seemed to be quite adequate in this condition. Full roll control inputs seemed to be in excess of what you would use during approach. I consider the lateral control good and would rate it a 2. There are other characteristics about the lateral control which reduce it to the 2, but as far as lateral control power is concerned it is quite adequate.

$\delta_W = 30°$. – I feel that this condition would be adequate for a precision-type approach in reasonable winds, without gusts. However, some of the maneuvering turns that I performed resulted in my striking the aileron limit. For precise small roll maneuvers I think the controls would have been adequate. For larger maneuvers I was touching 30° stops; so I would say for a hypothetical crosswind condition or gusty air you might be striking the 30° limit at times. I would give an overall rating of 3.5.

$\delta_W = 15°$. – I actually encountered the 15° stop during visual-flight-rules maneuvering to position the aircraft for a test series. Aileron control is very limited, and it is very poor even for visual-flight-rules flying. I would rate it as about a 6 or 6.5, primarily because of low lateral response and acceleration.

### Simulated Approaches at 134 Knots

$\delta_W = 45°$. – The lateral control power feels adequate for the approach condition at reference speed. It just does not appear that you normally require more than 45° wheel input for approach maneuvering. Although the roll power is a little lower when compared to that at 180 knots, the lateral control is adequate. Lateral control rating would be 2.

$\delta_W = 30°$. – The rolling response is down, so the pilot has a problem. For instrument-landing-system maneuvering, I think it would be usable; however, rapid, or even moderately rapid, wings-leveling maneuvers that might be required because of turbulence or other factors would put you right on the control limits. The pilot's commanded control reaches the stop, and you wait for the roll angle to change and the roll rate to develop. It has a very slow rate and slow acceleration. This is a degraded condition at the 30° control wheel stop. Rating--about a 4.5. We're evaluating smooth air, and turbulent air might cause these ratings to go lower.

$\delta_W = 15°$. – This roll control condition is very bad. I do not think you can fly an instrument-landing-system approach with this condition, even in smooth air. I think the normal deviations that one experiences during an instrument-landing-system approach would continually keep the pilot against the aileron control limits. This condition is very poor. I would rate it a degree lower than the 180-knot approach with 15° aileron limits. I call this one about an 8 rating.

## APPENDIX B

## TYPICAL PILOT COMMENTS ON ROLL EVALUATIONS DURING OFFSET APPROACHES - PILOT A

### Actual Approaches to Landings at 180 Knots

$\delta_W = 45°$. — There was very satisfactory lateral control during the 200-foot offset approach and landing. I did not have the feeling I was even close to the control-wheel stop. I was able to correct over and line up with the runway with quite satisfactory roll performance. I would rate that as a 2. It might be even a bit better than 2 from the control standpoint, so between a 1.5 and a 2. From the standpoint of the speed, it was entirely too much speed as far as float down the runway. You touch too far down the runway, because at that speed you are so far above reference speed. From the lateral control standpoint it was very good.

$\delta_W = 30°$. — I found when flying down the final approach that I had no tendency at all to hit the lateral control stops. However, when I started the offset correction, I immediately put in enough aileron to hit the stops and I got barely satisfactory rolling capability to return to the centerline. I would rate this as a 4. I hit the stops both correcting to the centerline and then correcting on the centerline once I reached it. I did on one occasion feel myself using a little rudder, but it could be done with the ailerons, so I would rate it as a 4. Again, the speed is too fast; it uses too much runway for the touchdown because of the speed. But the lateral control is a 4.

$\delta_W = 15°$. — On this approach I hit the stops only a couple of times during the approach, versus the 135-knot approach where I found myself hitting the stops quite often. When I started the correction from the offset, I immediately hit the stops on the initial correction. I was fairly conservative on bank angle. I did not let the bank angle get more than about 15° in the correction to the centerline when still about 40 or 50 feet in the air. I would rate this as a 7.5. It is certainly not very good but a bit better than at 135 knots. You can see the difference in the roll authority in the speed. The touchdown point is fairly far down the runway.

### Actual Approaches to Landings at 135 Knots

$\delta_W = 45°$. — Approaches were made with an approximate descent rate for an instrument landing system of about 700 feet a minute and with a 135-knot approach speed. At 200 feet altitude and at 200 feet offset to the right, we made a correction toward the runway. I had plenty of lateral control to make the correction to the runway centerline. Actual touchdown was about 1000 feet down the runway. I would rate the lateral control for this correction as 2. I had plenty of control, and there was no problem at all in lining up with the runway. In fact, I felt I could have cut the time down and still had a fairly good rating.

$\delta_W = 30°$. — As we crossed the 200-foot point, I started the correction back to the left and hit the control-wheel stop immediately. I was able to get satisfactory bank and initiated the roll to the left as I would like to have it; however, I felt there was a slight deficiency in roll rate when I started to correct back to the centerline. I again hit the stop with the right aileron in attempting to roll out on the centerline. This would be rated as a 4. It is not quite good enough, although on smoother conditions the offset is not too much to correct for. I think you'd probably get by all right. I did find myself using a little more runway to get lined up with the centerline. In other words, I was afraid to bank it over too much and therefore I ended by traveling farther down the runway to reach the centerline on touchdown.

$\underline{\delta_w = 15°}$. — With the 15° aileron stops, roll control was completely unsatisfactory. I found myself hitting the stops even on the final approach occasionally. Just to make a normal correction to keep the wings level, I hit the stops. When we made the correction back to the centerline, I immediately hit the stop, but I did not let the bank angle go as steep as I had on the first two approaches, and, actually, when I started to roll out on the centerline, I used a little rudder to assist in bringing the wing up. The lateral control was inadequate; even when I got the airplane on centerline and was in the flare, I hit the stops several times with the ailerons. In fact, at touchdown I had the aileron against the stop with the airplane in a slight wing-down condition. We touched slightly on one wheel, so I would rate this as somewhere around an 8. 5. It certainly is not satisfactory.

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